



Space Launch System Base Heating Test: Sub-Scale Rocket Engine/Motor Design, Development & Performance Analysis

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- ◆ **Test Program Background & Motivation**
- ◆ **ATA-002 Core-Stage Rocket Engine Module (CS-REM)**
 - Design, Development & Performance Analysis
- ◆ **ATA-002 Booster Stage Solid Rocket Motor (BSRM)**
 - Design, Development & Performance Analysis
- ◆ **CS-REM & BSRM Integrated Test**
- ◆ **Conclusions**



ATA-002 Technical Team



- ◆ **Aerosciences Branch, NASA Marshall Space Flight Center (MSFC)**
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- ◆ **Aerothermal/Aero-Optics Evaluation Center, CUBRC Inc.**
 - Aaron Dufrene², Nathan Solly, William Winter, Ron Parker, Zakery Carr, Dan Czora, Daniel Sargent and Christopher Halt
- ◆ **Thermal Analysis Branch, NASA Marshall Space Flight Center**
 - Darrell Gaddy, Adam Kimberlin and Wesley Lawler
- ◆ **Propellants and Propulsion Branch, NASA Glenn Research Center**
 - Bill Marshall
- ◆ **Plasma Processes Inc.**
 - Tim McKechnie and George Thom

¹ NASA Technical Lead

² CUBRC Technical Lead



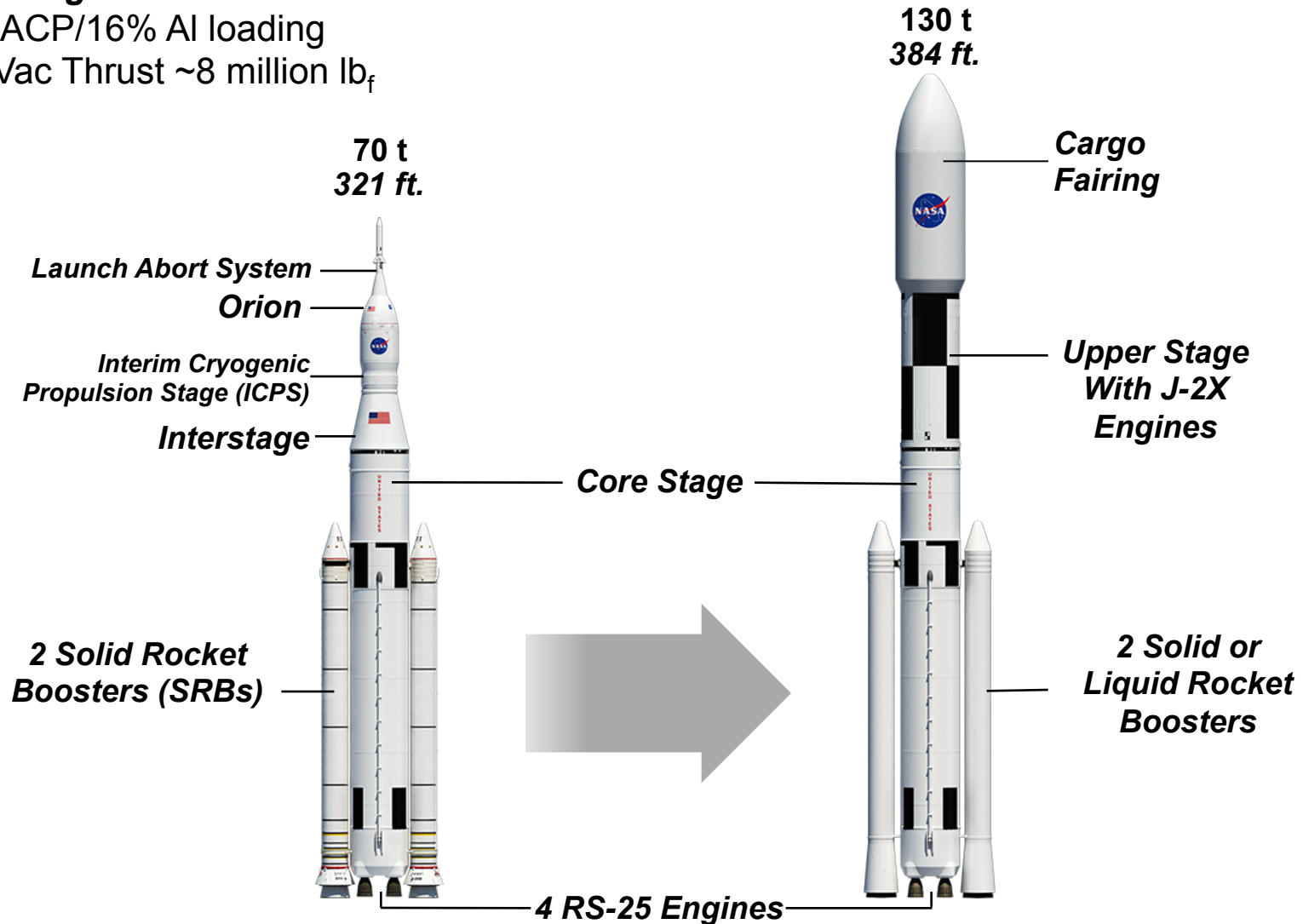
Space Launch System (SLS) Architecture



RS-25 Engines: LOX/LH2

SRB: ACP/16% Al loading

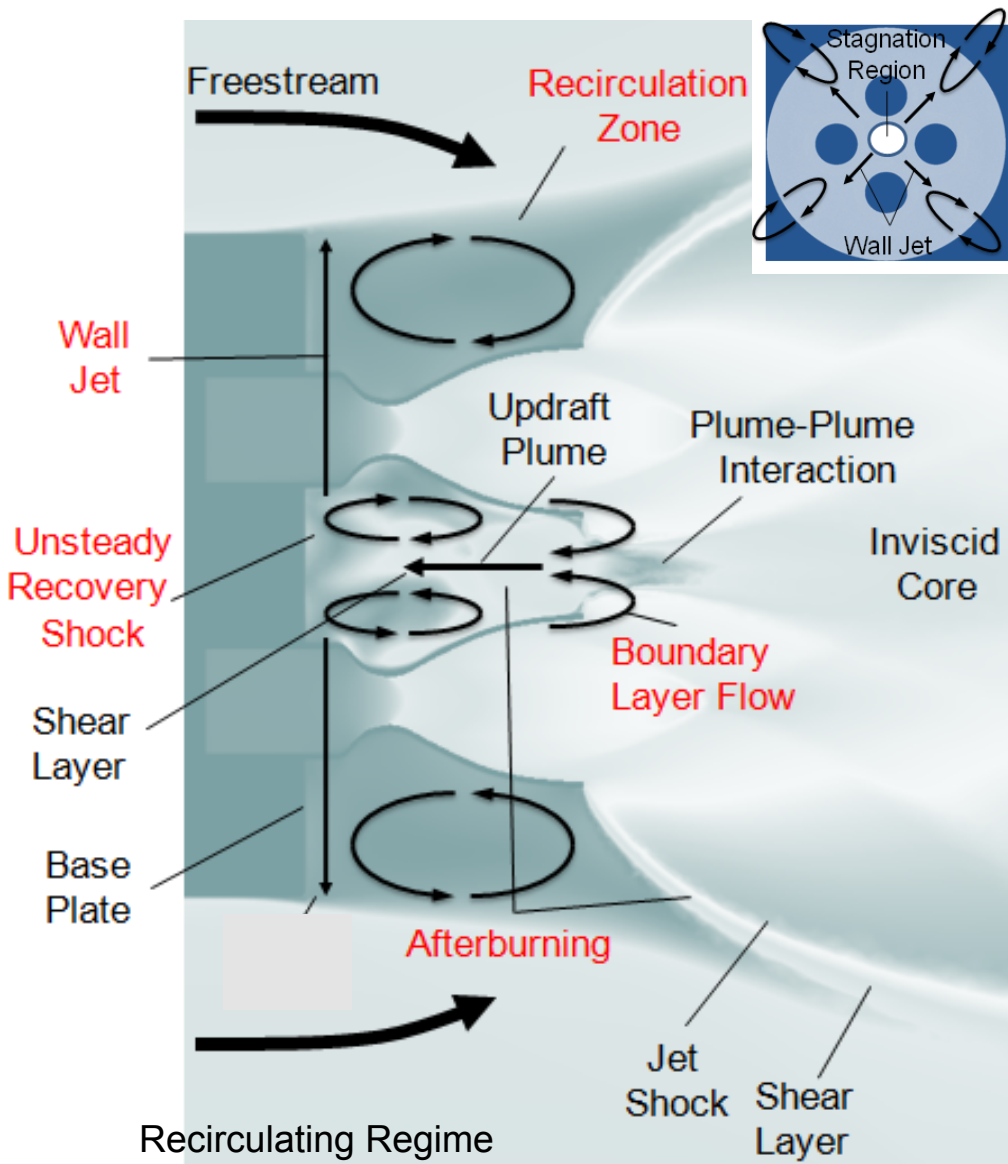
Total Vac Thrust ~8 million lb_f



2017 EM-1

- ◆ **Six hot rocket plumes expanding and interacting near the vehicle base**
 - Potential to generate high thermal environments within base and nozzles
- ◆ **Base flows demonstrate complex flow physics**
 - No pure analytical methods have been developed for adequate prediction
- ◆ **New base geometry and performance requirements for SLS**
 - Cannot blindly use heritage data
- ◆ **CFD and semi-empirical methodologies show poor comparisons**
 - Significant deviations in magnitude and trends
- ◆ **Accurate base flow environment prediction needed to efficiently size TPS**
 - Decreases vehicle cost and improves crew safety





Limited numerical and analytical studies have been conducted to fully characterize multi-plume base heating.

For the following reasons:

1. Complex
2. Unsteady
3. Many interacting flow features
4. Leads to many different trends, distributions and deltas

Base Flow Regimes:

Aspirating – Freestream air is entrained by the non-interacting rocket plumes (cooling)

Transitional – slight interactions by adjacent plumes leads to updraft plume component and downward aspirating jet

Recirculating – large interactions by highly expansive plumes leads to predominantly an updraft plume (heating)



ATA-002 SLS Pathfinder Test Program



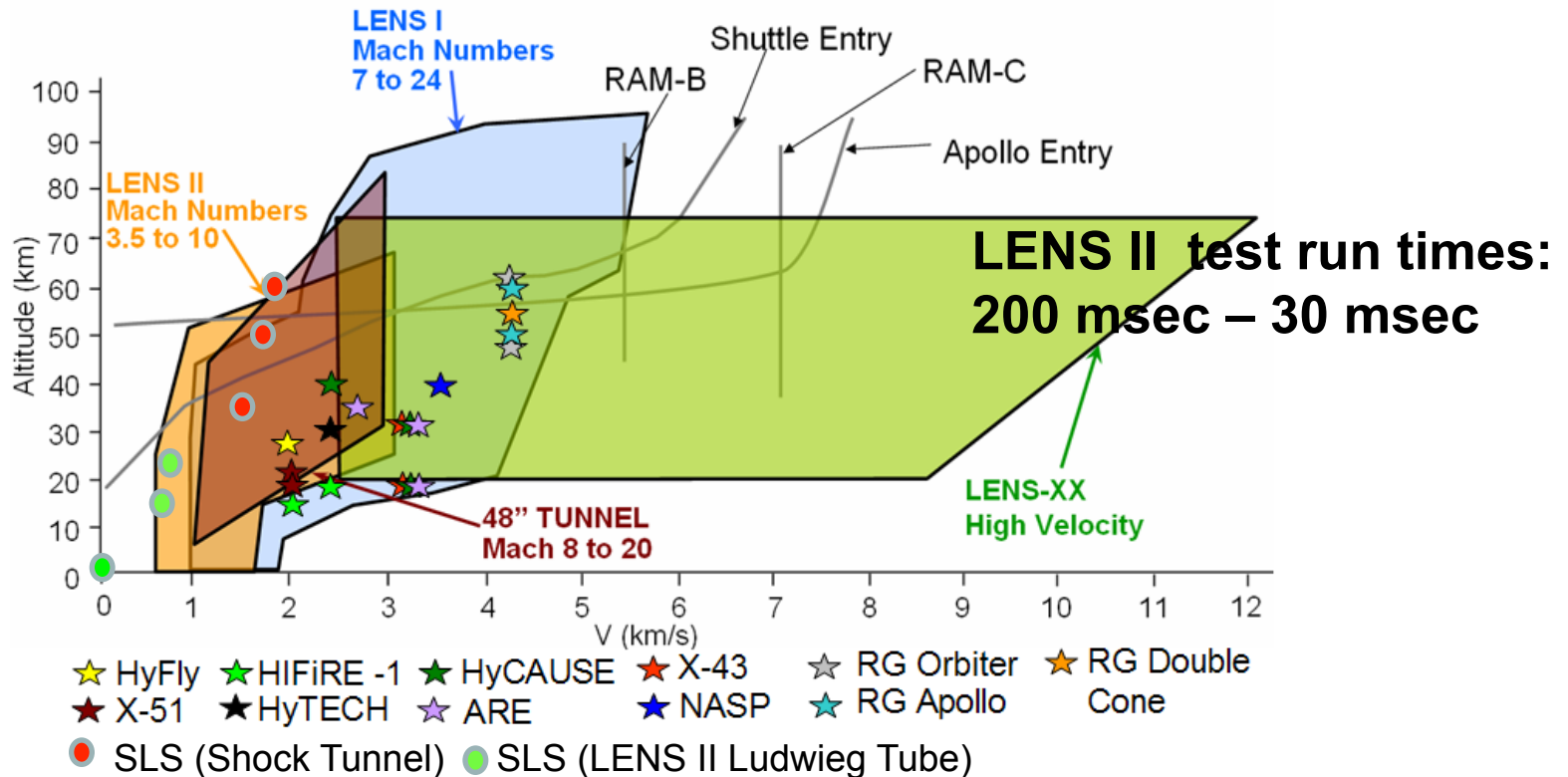
- ◆ **ATA-002 Base Heating Test Program is broken down into two sub-test programs: (1) Pathfinder and (2) Main Base Heating Test**
- ◆ **Goal is to develop sub-scale SLS propulsion systems similar to full-scale flight system to be used for short-duration (~100 msec) base heating tests.**
- ◆ **The Pathfinder Program has many difficult challenges:**
 - Highly complex test program (simulate solid & liquid propulsion systems)
 - Short-duration testing
 - Different configuration/performance than Shuttle Base Heating Models
 - Not attempted in 40 years
 - Limited heritage technical resources (engineers/technicians/components)
 - Limited funding & short schedule as compared to heritage test programs
- ◆ **Pathfinder Test Program is the main focus of this paper**



◆ **Main Goal: To measure base flow and heating characteristics for the SLS1000x vehicle and to scale these measurements for flight predictions**

◆ **Test Requirements**

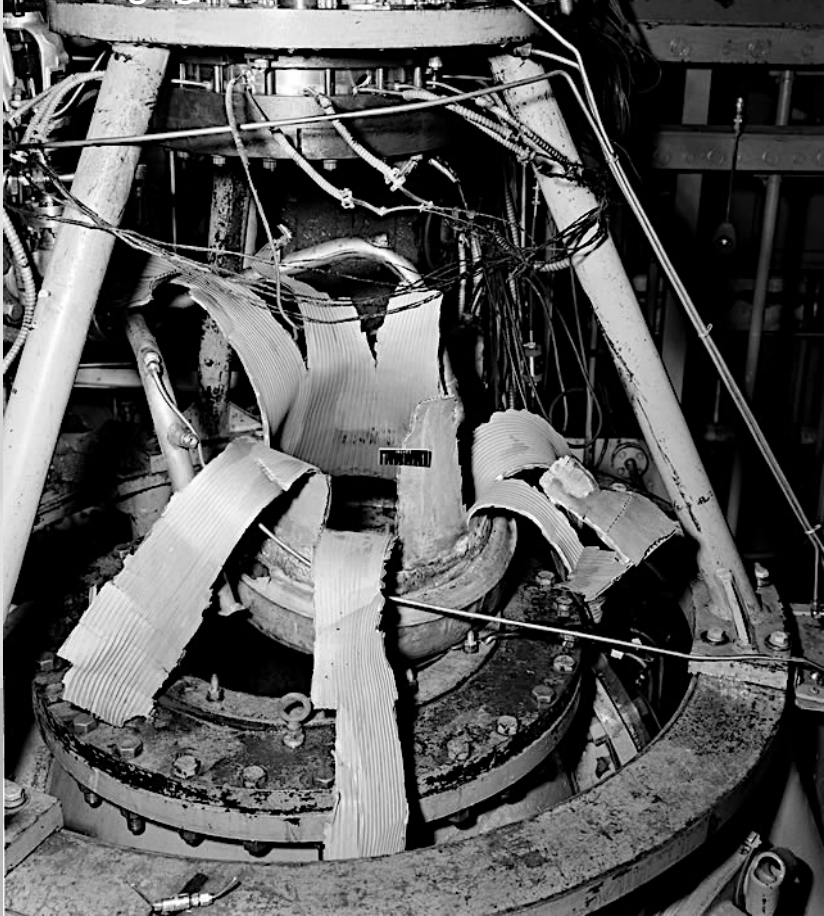
- 2% SLS-1000x Model
- Test in short-duration test facility – CUBRC LENS II
- Simulated altitude: 45 kft to 200 kft, Mach 2.5 to 5.5
- Configuration: full-stack and core-only stage space flight conditions
- Test Duration: ~100 msec steady-state time window
- No gimbaling of engines/motors
- No Angle of Attack
- Test Engine-Out Case
- 200 measurements within base and external nozzles



Rocket Combustion Chamber
Failure During Ignition Start



Rocket Combustion Chamber Failure
During Ignition Start



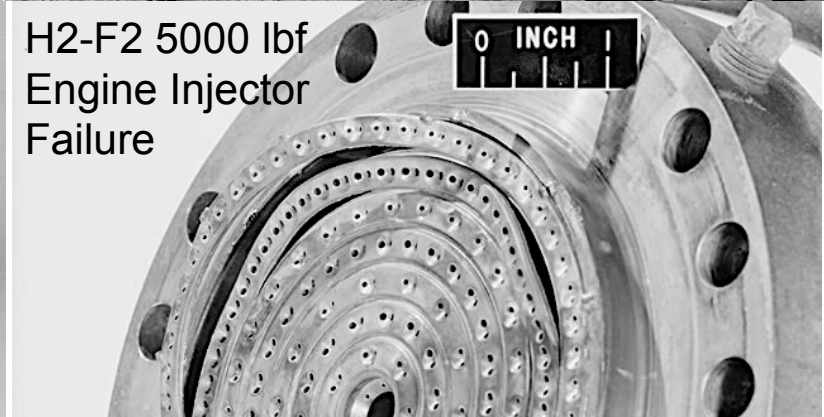
H2-F2 5000 lbf Engine Injector
Failure



Rocket Engine Injector
Failure During Ignition
Start

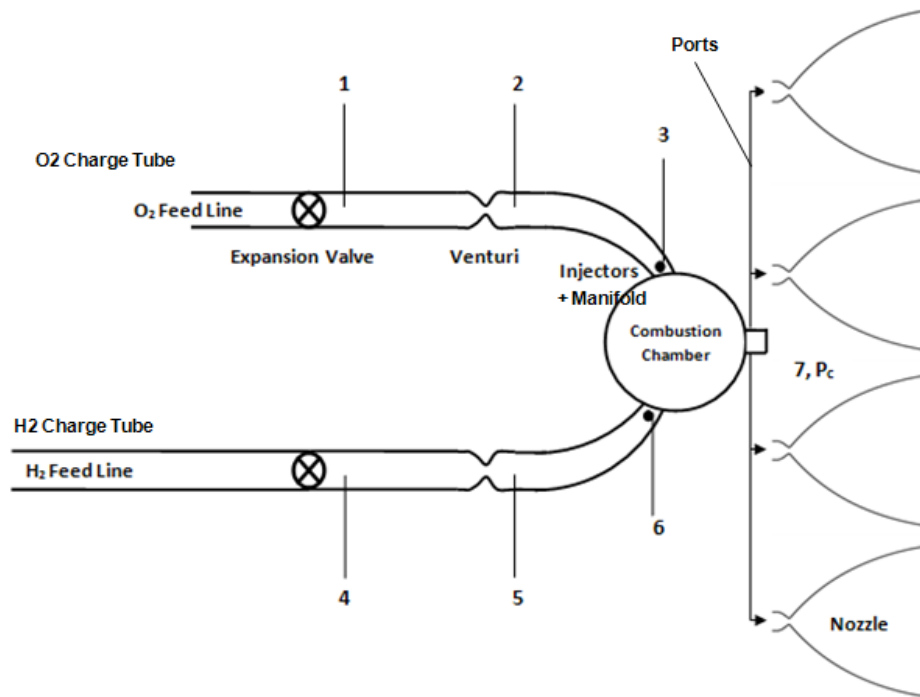
**ROCKET
SCIENCE IS
HARD**

H2-F2 5000 lbf
Engine Injector
Failure



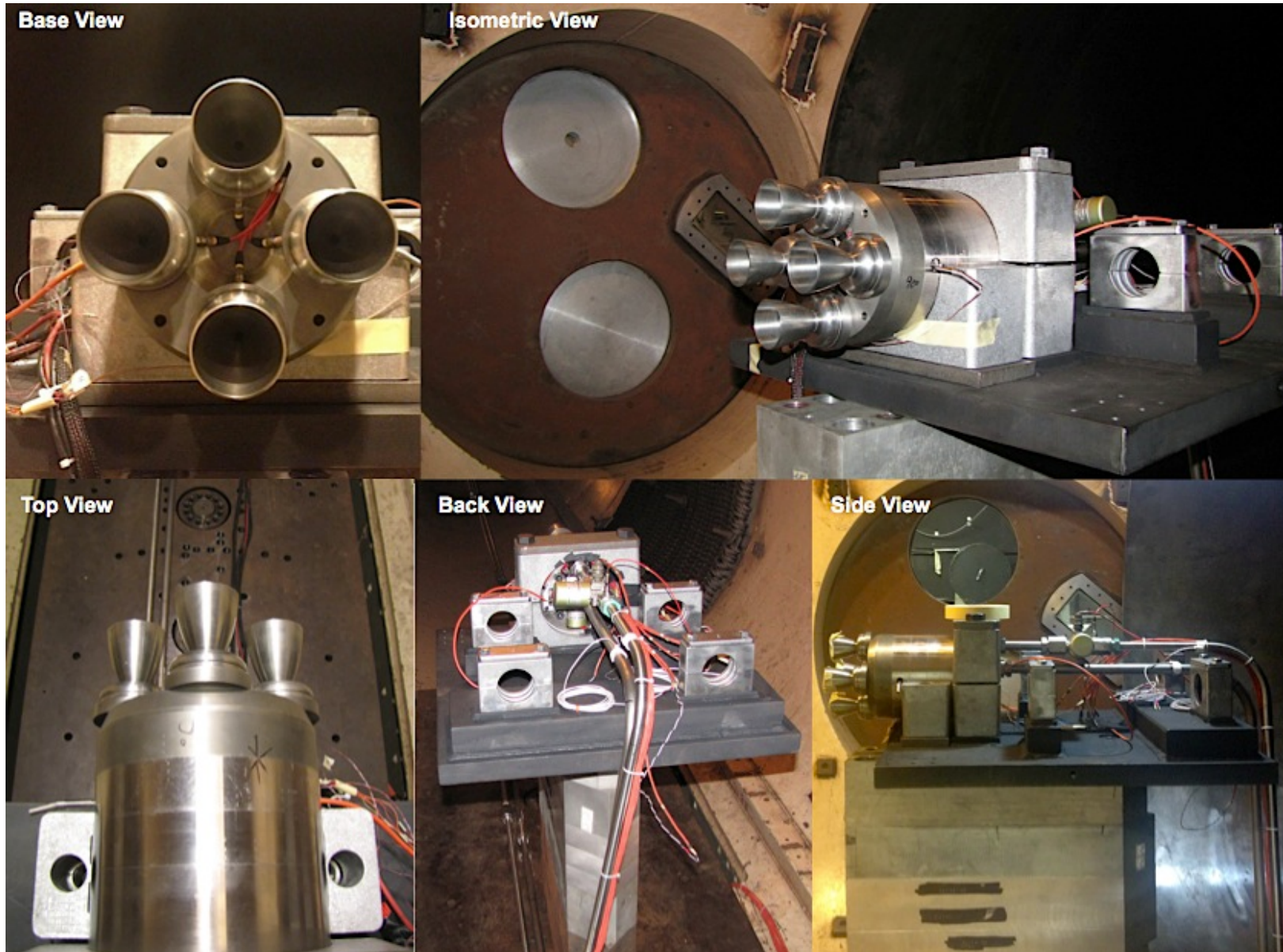


ATA-002 Core-Stage (CS) Rocket Engine Module (REM) Design



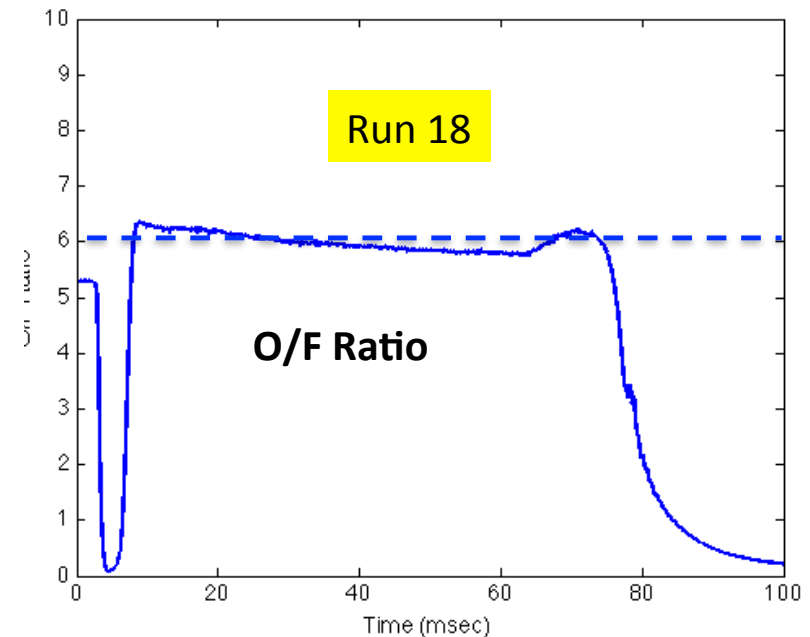
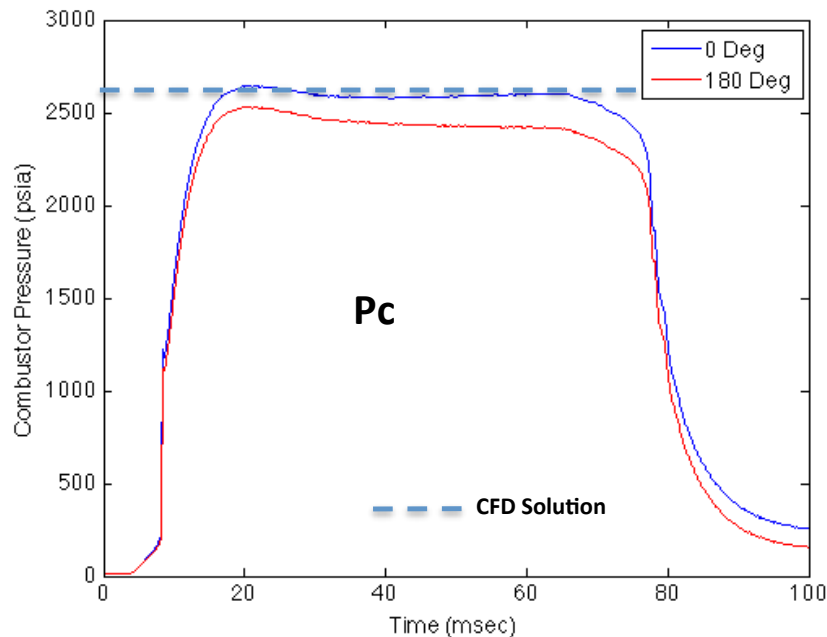
Internal engine instrumentation installed by CUBRC to determine performance and validation of design methodology

- ◆ **Initial design based on in-house engineering codes and assessment:**
 - QICE – engine component sizing/design & performance
 - IBFF – state parameter time history prediction code of the model performance
 - Valve-venturi design & performance code
 - Heritage design comparisons
- ◆ **Final design based on in-house CFD internal flow modeling of propulsion system:**
 - Combustion Instability Assessment
 - CUBRC developed CAD geometry
 - Loci-CHEM – CFD Code with finite-rate chemistry
 - Led to re-design of GO2 manifold system and combustor
 - Provided performance curves
- ◆ **Final design based on thermal modeling**
 - Patran/Sinda G – Led to nozzle material and coating selection
- ◆ **Developed nozzle specific enthalpy flow code**
 - Determines the nozzle exit specific enthalpy profile, the required test duration and material selection
- ◆ **Loads FEA**
- ◆ **Extensive design & analysis efforts were done to minimize cost and schedule risks.**





ATA-002 CS-REM Performance Analysis



◆ All performance parameters:

- Have met design requirements
- Show good agreement with EV33 prediction and design tools
- Show similarity to full-scale RS-25D engine system

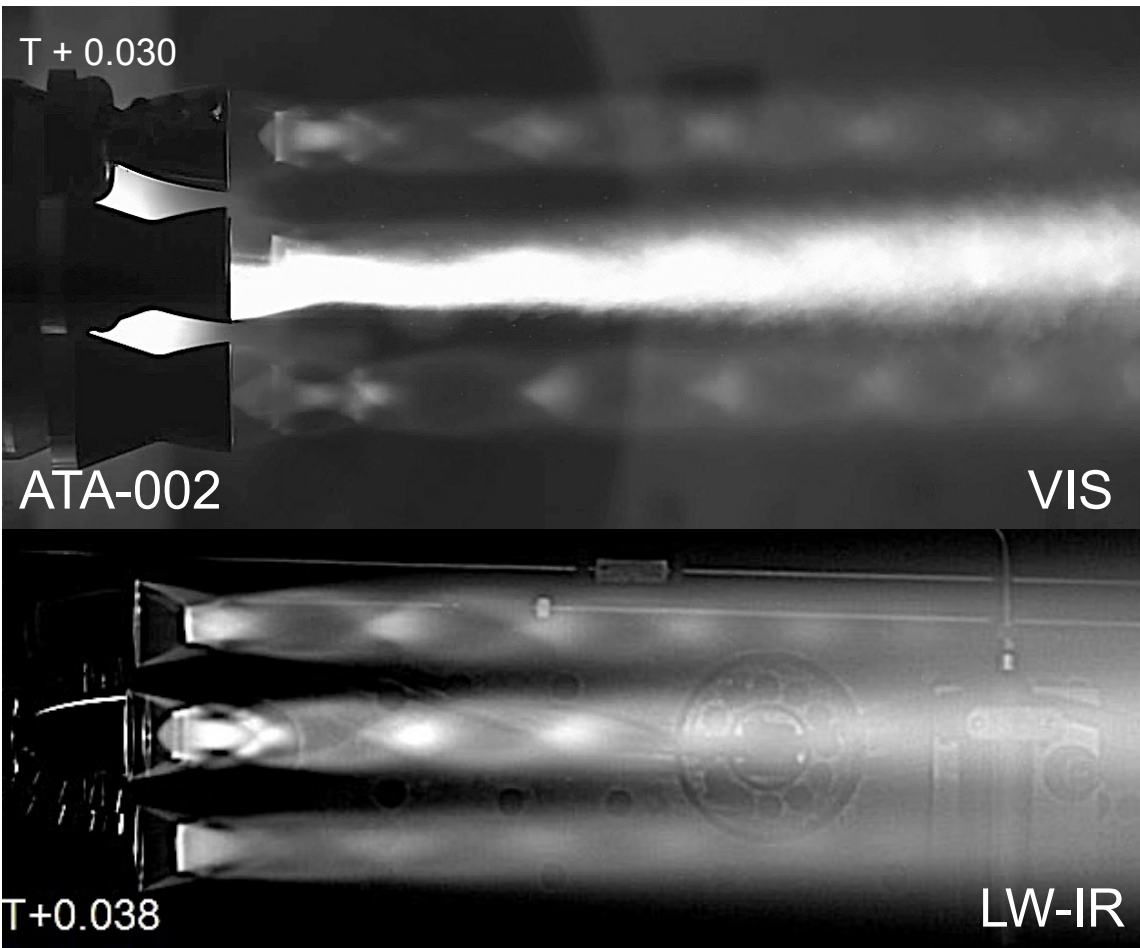
◆ All engine pressure measurements obtained by PCB-111 quartz gauge



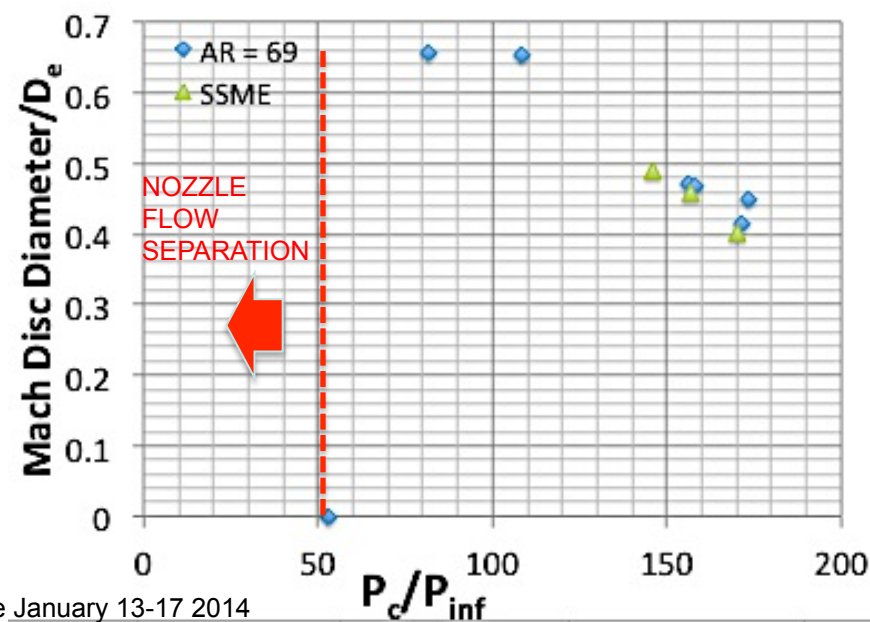
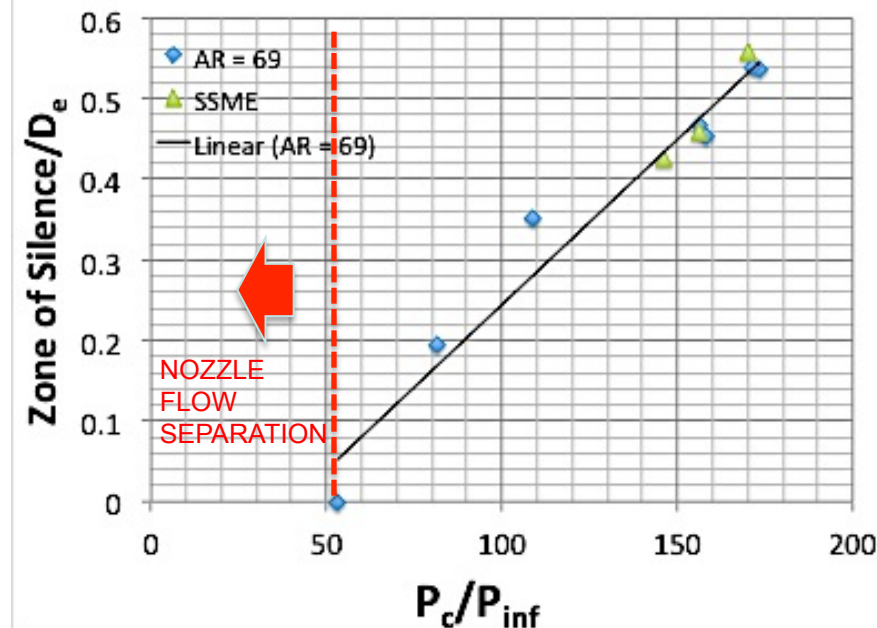
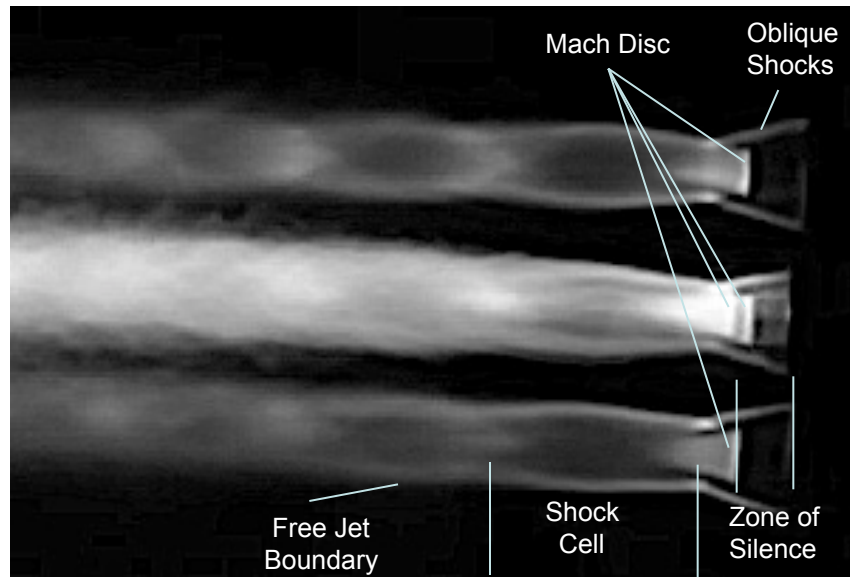
ATA-002 CS-REM Hot-Fire Test



- ◆ MSFC camera provided high-resolution (1280 px x 800 px) and high frame-rate (16000 Hz) visible (VIS) video of CS-REM hot-fire tests
- ◆ MSFC infra-red (IR) camera provided long-wave IR video of CS-REM hot-fire tests
- ◆ Able to adequately determine the shock structure and flow physics

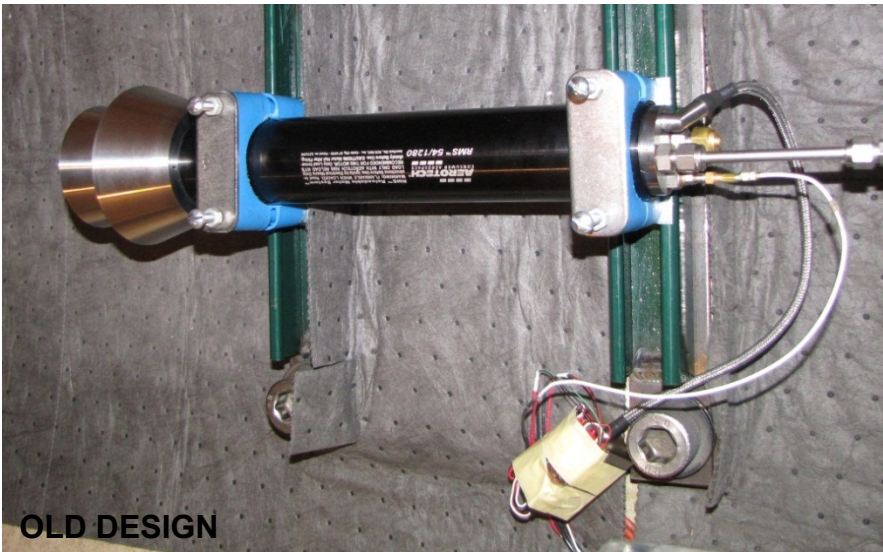


- ◆ SSME VIS video taken during static sea-level testing at NASA Stennis Space Center

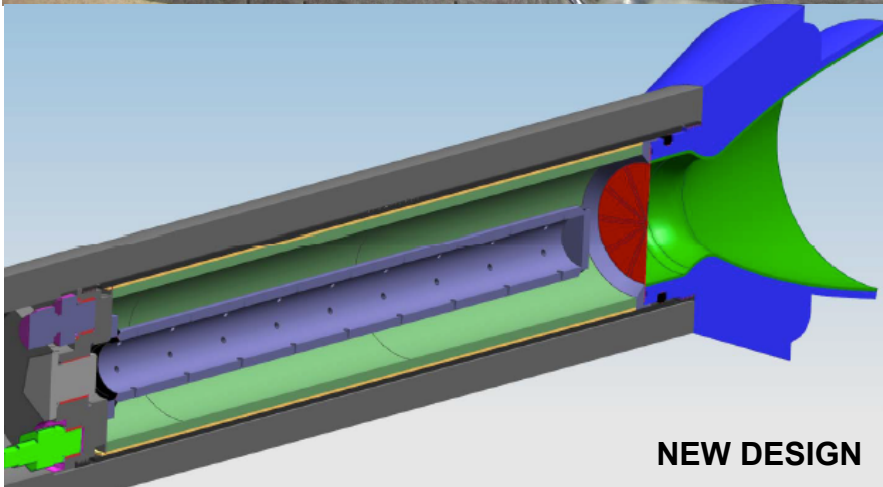


- ◆ **CS-REM plumes:**
 - Are over-expanded at sea-level conditions
 - Free-jet boundary converge toward the centerline
 - Develops a characteristic Mach disc
 - No plume-plume interactions observed
- ◆ **CS-REM shock structure and flow physics show good similarity with full-scale RS-25D (SSME) systems.**
 - Important to obtain high-fidelity base heating data
- ◆ **Zone of silence normalized distance increases linearly with chamber pressure.**

ATA-002 Booster Solid Rocket Motor (BSRM) Design



OLD DESIGN



NEW DESIGN

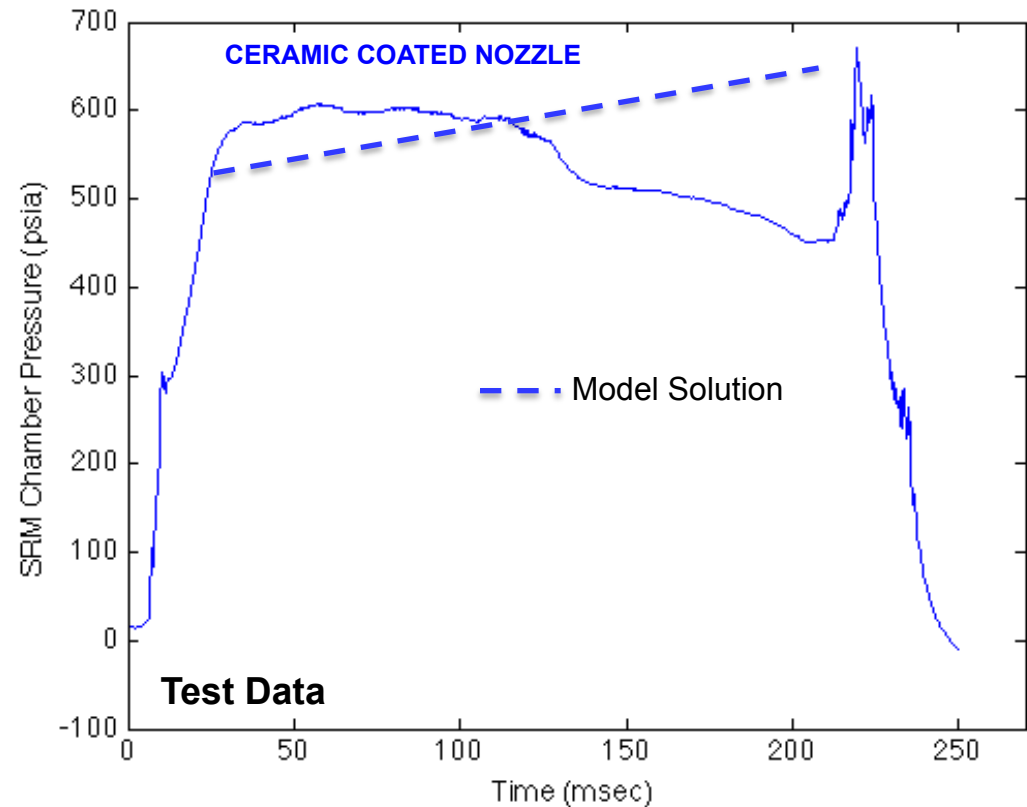
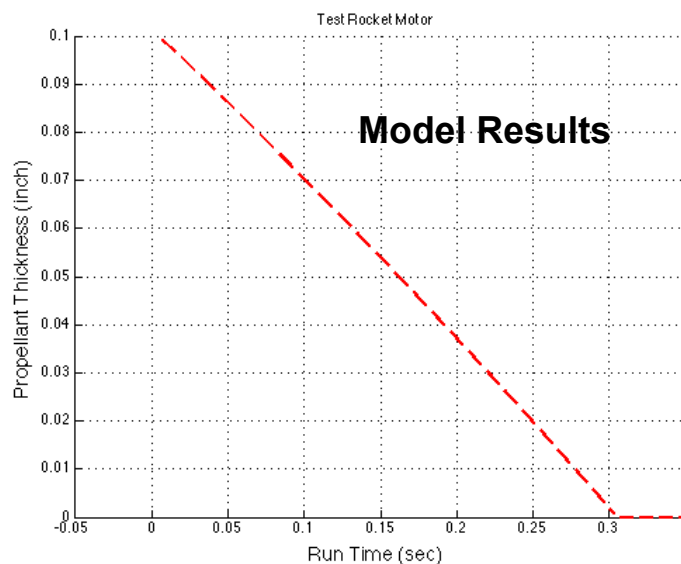
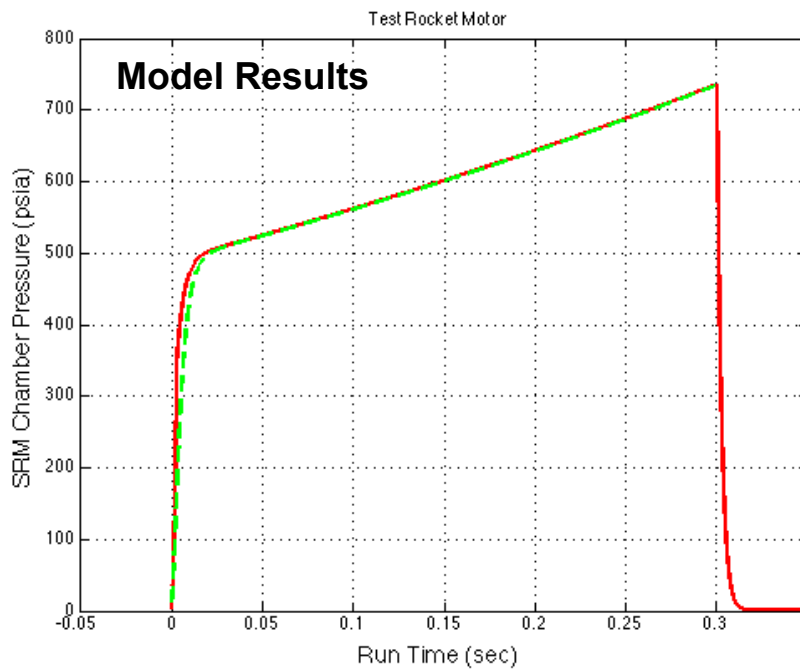
- ◆ **Initial design based on in-house engineering codes:**
 - Conservation of mass sizing/design & performance code
 - Heritage design comparisons
- ◆ **Final design based on thermal modeling**
 - Patran/Sinda G – Led to nozzle material and coating selection
- ◆ **Developed nozzle specific enthalpy flow code**
 - Determines the nozzle exit specific enthalpy profile, the required test duration and material selection
- **Initial design did not meet performance requirements due to significant ignition delay**
 - Required trial-and-error igniter options to obtain desired ignition response time
- **CUBRC with NASA MSFC collaboration developed an innovative igniter to meet design requirements**

Internal engine instrumentation installed by CUBRC to determine performance and validation of design methodology





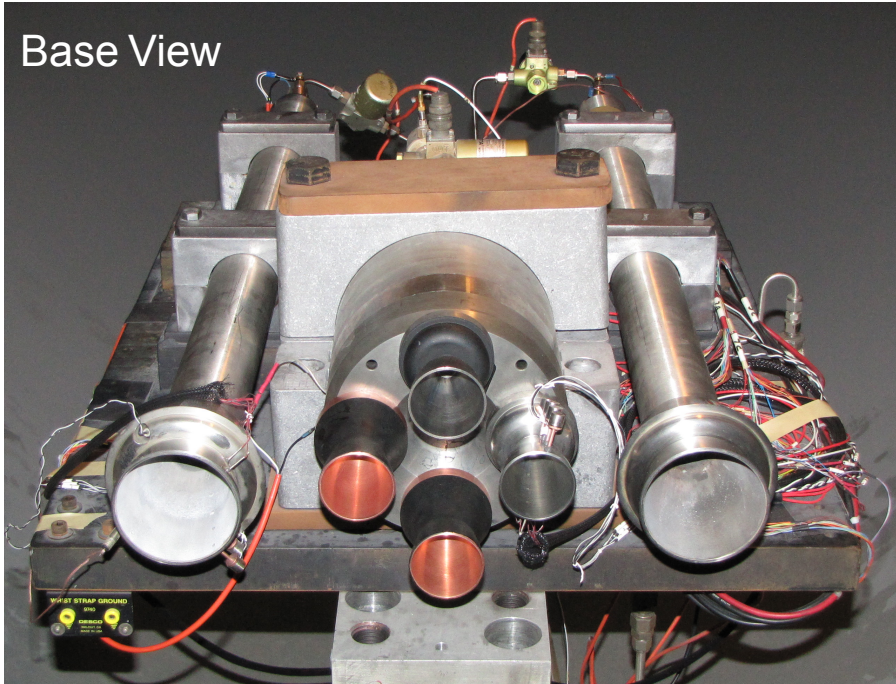
ATA-002 BSRM Performance Analysis



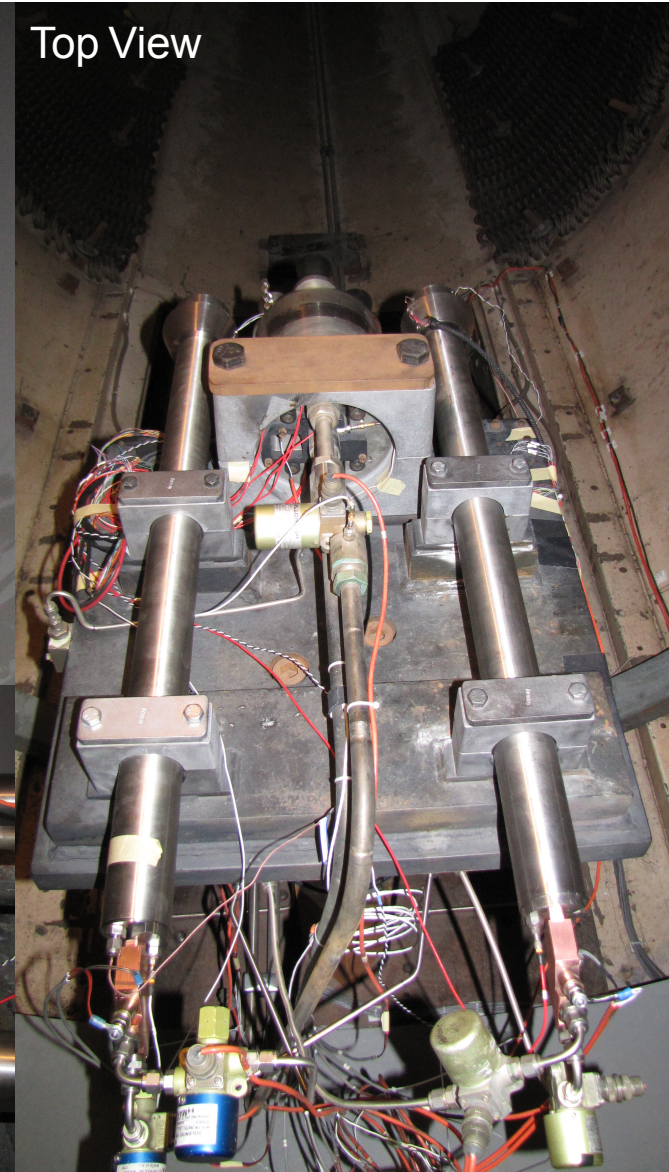
SRM Run 006
PROPELLANT X

	Pc Avg	T-shutdown	tau	Burn mass
	psia	msec	msec	kg
Model	550	300	25	0.42
Test	600	250	34	0.42

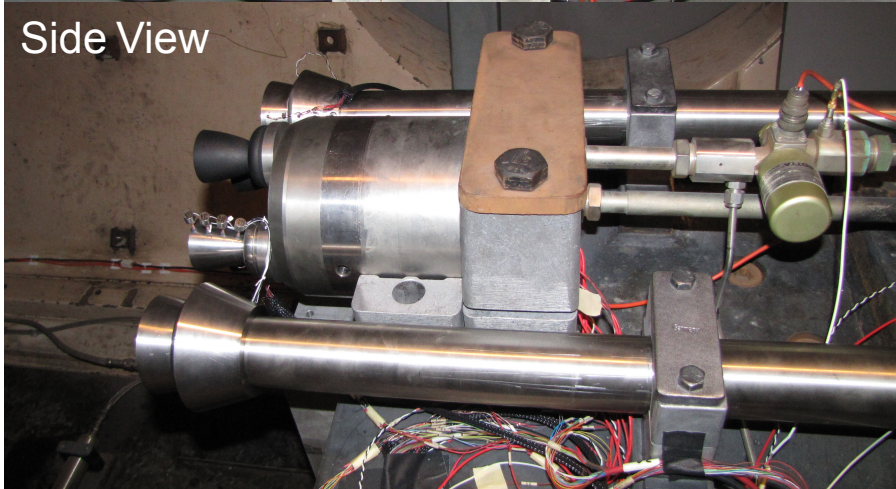
Base View



Top View



Side View





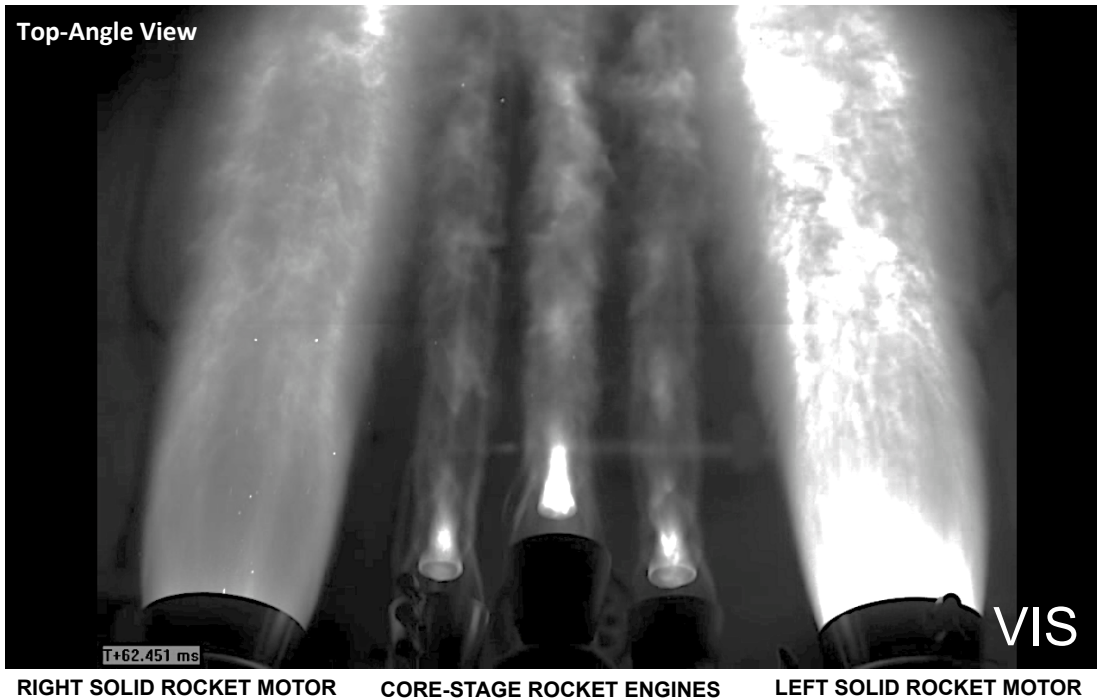
Integrated Core/Booster Stage Hot-Fire Test





Integrated Core/Booster Stage Rocket Plumes

Top-Angle View

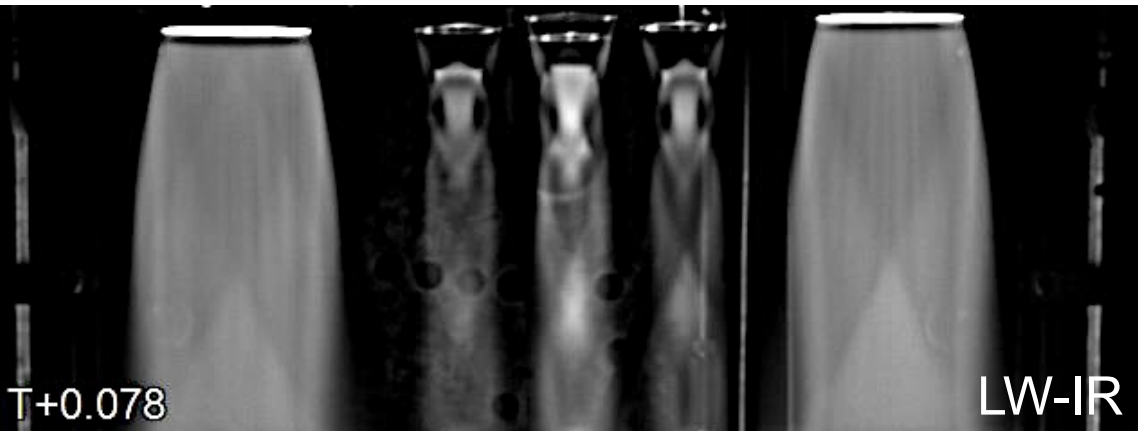


RIGHT SOLID ROCKET MOTOR

CORE-STAGE ROCKET ENGINES

LEFT SOLID ROCKET MOTOR

- ◆ CUBRC VIS camera 4700 fps at 800 px x 600 px resolution
- ◆ VIS and LW-IR videos show CS-REM and BSRM plumes all-firing together as designed.
- ◆ All CS-REM plume Mach discs are within the same location and have the same diameter
- ◆ Plumes are fully-developed and steady in less than 35 msec
- ◆ Plume diameters are similar between the left and right BSRMs
- ◆ No flow asymmetry observed
- ◆ Showed propulsion designs are successful.





Conclusions



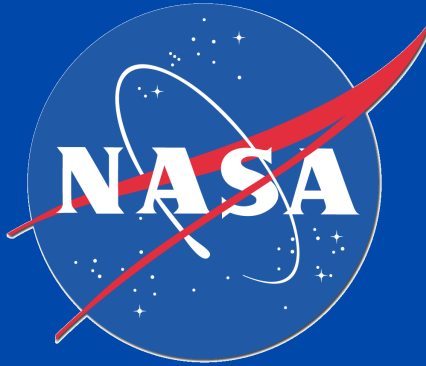
- ◆ **ATA-002 Technical Team has successfully designed, developed, tested and assessed the SLS Pathfinder propulsion systems for the Main Base Heating Test Program.**
- ◆ **Major Outcomes of the Pathfinder Test Program:**
 - Reach 90% of full-scale chamber pressure
 - Achieved all engine/motor design parameter requirements
 - Reach steady plume flow behavior in less than 35 msec
 - Steady chamber pressure for 60 to 100 msec during engine/motor operation
 - Similar model engine/motor performance to full-scale SLS system
 - Mitigated nozzle throat and combustor thermal erosion
 - Test data shows good agreement with numerical prediction codes
- ◆ **Next phase of the ATA-002 Test Program**
 - Design & development of the SLS OML for the Main Base Heating Test
 - Tweak BSRM design to optimize performance
 - Tweak CS-REM design to increase robustness
- ◆ **MSFC Aerosciences and CUBRC have the capability to develop sub-scale propulsion systems to meet desired performance requirements for short-duration testing.**



Acknowledgement & References



- ◆ *Special thanks to Mr. Mark D'Agostino (Aerosciences Branch Chief), Dr. Chris Morris (Aerothermal Team Lead), Mr. Jeff Vizcaino and EV33 for technical and programmatic support.*
- ◆ Mehta et al (2013), Numerical Base Heating Sensitivity Study for a Four-Rocket Engine Core Configuration, *J. of Spacecraft & Rockets*, Vol. 50, No.3.
- ◆ Detail information on propulsion design, fabrication, test and performance analysis will be published as a NASA Technical Memorandum.



Thank You

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